CIRCULATION CONTROL FOR THE ROTORS OF LARGE HORIZONTAL AXIS WIND TURBINES

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Circulation control, augmenting aerofoil lift and reducing drag using air jets is long established but little considered for wind turbine applications. This is a top-level exploration of the basic concept which involves a substantial part of the rotor blade having low solidity, elliptical sections which generate little lift and drag when passive, greatly moderating extreme storm loads when the rotor is idling. The CC rotor can then be expanded in diameter by ~ 30% within the same loading envelop of a standard rotor with gain in energy capture to compensate for added cost in the rotor systems.

Keywords: wind turbine, circulation control, rotor, elliptical aerofoil, extreme loads

INTRODUCTION

A thin jet of air discharged tangential to the surface near the trailing edge of an aerofoil has reduced static pressure and will attract the general flow to the jet (Fig 1) generating enhanced lift.

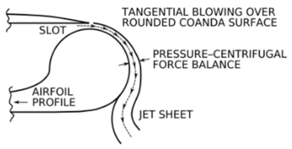


Fig.1 Circulation control concept

This circulation control (CC) has been developed over 60 years [1], [2] and employed in innovative aircraft designs such as the X Wing aircraft (vertical take-off like a helicopter and forward flight like an aeroplane) and the NOTAR helicopter which used air jets to react the main rotor torque rather than tail rotors. CC could readily be dismissed for the wind turbine application. It requires additional systems for control and pressurization of the air jets and also imposes new structural demands on the rotor. Slots for discharge of the air jets must be dimensionally accurate and maintain performance in operation coping with elastic deformation of the blades.

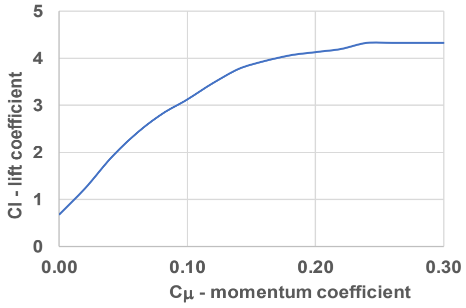


Fig.2 Maximum lift of a 30% thick elliptical CC aerofoil

After consideration of the energy loss associated with air jet pumping as traded against superior control of aerofoil characteristics and drag reversal, there may be little or no direct benefit to rotor power performance.CC, however, enables load regulation to an extent far beyond other rotor control concepts. Thick elliptical (30% thickness to chord ratio) aerofoil sections are preferred for the CC rotor design. They are much more efficient structurally than more slender standard aerofoil sections with sharp trailing edges, they are (see Fig.2) of comparatively low maximum lift when the air jets are off ($Cl \sim 0.7$) and they may produce very high lift ($Cl \sim 4$) when the jets are active.

ROTOR EXPANSION AND EXTREME LOADS

A standard rotor of 100m diameter and 3 MW rating is chosen as baseline for comparison purposes. The concept for exploitation of circulation control on a wind turbine rotor is, in comparison with this standard rotor, to enable a large expansion of the rotor diameter and consequent power and energy gain without exceeding any design driving loads of the baseline. Optimum blade design is related to the product, cCl_d where c is chord width and Cl_d is the design lift coefficient for a given blade section. Thus, compared to the baseline design, since the CC sections can produce Cl values 3 or 4 times greater than standard aerofoils, the chord widths of the CC rotor may in principle be reduced by factors up to 3 or more. As a first step, extreme storm loads on the idling rotor are considered. In this case, the air jets of the CC rotor are inactive and loads on the CC sections can be evaluated from passive lift and drag characteristics.

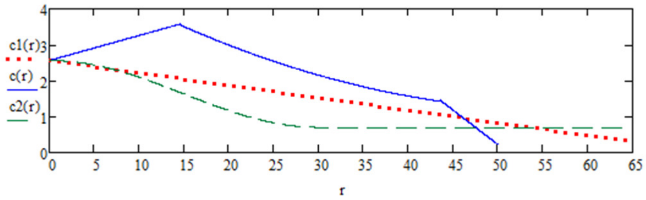


Fig. 3 Planforms of baseline and extended CC rotors

In Fig 3 the baseline, 50 m radius rotor is compared with possible CC planforms of 65 m radius. In Fig.3 $c1(r)$ is a chord distribution of simple linear taper and $c2(r)$ is a distribution providing a section of constant chord width which may possibly simplify CC blade manufacture. These planforms are indicative only with the idea that, in normal operation, the required optimum lift on CC sections of much less chord than baseline can be achieved by appropriate air jet blowing. Based on a wind speed of 70 m/s and a simple steady state calculation, extreme bending moments and thrust forces of the 3 planforms are compared in Fig. 4 and 5. In these figures the abscissa is the radius fraction, $x = r/R$, where r is radial position and R is tip radius. Comparing in this way reveals that the CC designs have reduced loading both at mid span and around the blade root, which are often critical areas for blade design, and at rotor centerline which is critical for loads passed into the rest of the system. At this stage, the CC planform designs have not yet been validated as good designs for general operation. The main aim is to show that a wide range of much reduced solidity CC rotors can regulate extreme storm loads within baseline levels with as much as 30% expansion of rotor diameter.

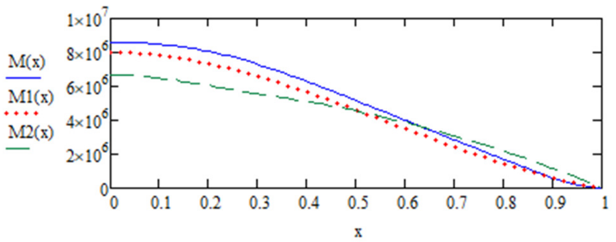


Fig.4 Blade out of plane bending moments [Nm]

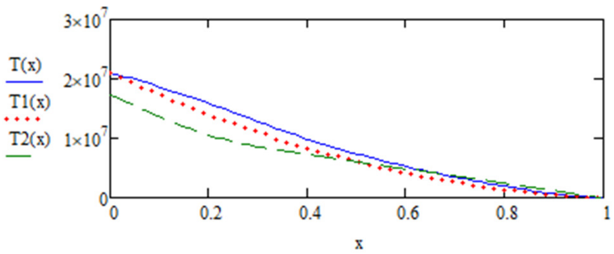


Fig.5 Blade thrust force [N]

Although this comparison is based on simplified calculations of steady loading, it is a fair indication of the potential to regulate extreme loading on a rotor idling in severe storm conditions. In normal operation of the rotor, it is expected to have the usual pitch system and the torque reaction control of a variable speed drive. The circulation control then provides vital additional capability for fast response to regulate loads of the expanded rotor within baseline levels.

A MODEL FOR CC ROTOR DESIGN

Adapted Blade Element Momentum (BEM) Model

The basis of a preliminary steady state model of a CC rotor is standard BEM theory. Although the maximization of rotor power based on an axial induction of $1/3$ may not be rigorously correct for the CC rotor which has an element of reaction jet drive, this was used as a starting point. The tangential induction is very small on most of the span of typical large electricity producing wind turbines with rotor design tip speed ratios above 6 and most typically around 8 and it was initially ignored. The basis of the performance modelling was to develop tables of aerofoil data as a function of both angle of attack and slot momentum coefficient. This allowed the lift and drag coefficients to be determined for any blade section at any chosen level of jet blowing. These tables are essential for dynamic modelling. However, as a simplification in the initial steady state model, only CC data for zero incidence was used and the blade twist distribution was determined to achieve this in optimum operation at design tip speed ratio.

Jet Power Requirements

In pumping air radially along a rotating blade, there are obviously friction losses in the duct but also some benefit from centrifugal force. It is readily shown that the pressure addition from centrifugal force exactly matches the stagnation pressure on the section where jet discharge takes place. A simple model of the pressure difference at radius fraction, x, is then given by Equation 1.

$$\Delta p(x) = \Delta p_0\left[1-(1-\eta_d)(x-x_f)\right] + 0.5\rho(x\omega R)^2 \qquad (1)$$

In Equation 1, $\Delta p_0, \eta_d, x_f, \rho, \omega$ are respectively, fan pressure rise, duct efficiency, radius fraction of fan discharge, air density and rotor angular speed. The jet velocity discharging at radius fraction, x, is given as;

$$V_{jet}(x) = \sqrt{2\frac{R_{mole}}{\rho V_{mole}}\left\{\frac{T_d}{\mu}\left(1-\xi^{\frac{\gamma-1}{\gamma}}\right)\right\}} \qquad (2)$$

In Equation 2, R_{mole}, V_{mole}, T_d, ξ, γ, are then respectively the molar gas constant, molar volume, duct air absolute temperature, the ratio of atmospheric pressure to total duct pressure and the ratio of specific heat of air at constant pressure to that at constant volume. A distribution of h/c, the slot height to section chord width ratio is then developed considering its effect on blade planform and section lift capability as influenced by the slot momentum coefficient, C_μ which is calculated as;

$$C_\mu(x) = 2\frac{h}{c}(x)\left[\frac{1}{\xi(x)}\right]^{\frac{1}{\gamma}}\left[V_r(x)\right]^2 \qquad (3)$$

In Equation 3, $V_r(x)$ is the ratio of jet velocity to section inflow velocity. In order to calculate jet power demand, the mass flow of the jet through a section of spanwise extent, Δr, is calculated as;

$$\dot{m}_{jet}(x) = h(x)\Delta r\left[p_\infty + \Delta p(x)\right]\sqrt{\frac{2\left[\{\xi(x)\}^{\frac{2}{\gamma}} - \{\xi(x)\}^{\frac{\gamma+1}{\gamma}}\right]}{[\gamma/(\gamma-1)]R_{eq}T_d}} \qquad (4)$$

The jet flow before discharge is travelling radially in the rotating reference frame of the blade. It is forced by the blade duct walls into a spiral path as viewed from a fixed frame and thereby exerts an opposite reaction force tending to brake the rotor. This Coriolis force absorbs power, P_{cor} determined as;

$$P_{cor}(x) = \omega^2 \dot{m}_{jet}(x)\, x^2 R^2 \tag{5}$$

Net Power Generated

Integrating over the span of the blade, the pumping power demand is determined as the sum of the powers providing the required jet discharge velocity at each radial station plus that required to compensate for the Coriolis braking effect. The positive power produced by lift and drag is derived by the usual BEM analysis of blade element in-plane force leading to the elemental torque and power contribution that is integrated over the span. Retaining the standard definitions of lift and drag coefficients, as determined in 2D wind tunnel tests, the drag coefficient of CC blade sections is often negative due to a driving force from jet reaction The power of the baseline rotor in the same operating state and external conditions as the CC rotor (i.e. at optimum tip speed ratio in a steady wind speed below rated power) is determined by an exactly parallel analysis. A common drive train efficiency of 0.93 is assumed for all rotor designs.

OPERATIONAL CONCEPTS

Fixed speed operation with an induction generator is feasible as the classic historic problems with variable pitch and fixed speed are alleviated by the fast control capability of the air jets. Also a combination of stall regulation and CC could avoid a pitch system and eliminate many of the disadvantages of stall regulation in respect of high loads above rated wind speed, aerofoil roughness sensitivity and energy capture compromises below rated power. However, it would still leave the problem of providing a fail-safe system for prevention of overspeed. This preliminary study focusses on ideal variable speed operation, as other modes of operation are more complex to design. In a large wind turbine system, possibly with direct drive PMG, it would be natural to operate with variable pitch and variable speed. Associated with the enhanced power of the expanded CC rotor is a commensurate increase in rotor thrust. This increase does not affect design in low wind speed operation and a familiar thrust shaving in wind speeds near rated wind speed, by blade pitching, reduced blowing or a combination of both, can regulate thrust within the peak level of the baseline rotor. This sort of load regulation (using blade pitching) is commonplace in commercial wind turbine design. It implies some loss of power in wind speeds near rated. It was found that thrust regulation by a combination of blowing power regulation and pitching is satisfactory and significantly better for power performance than pitch regulation alone.

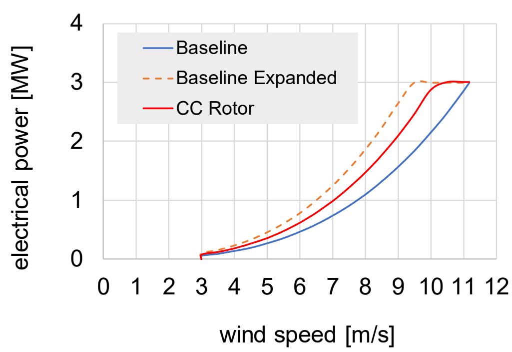
DESIGN FOR MANUFACTURE

The elliptical aerofoils sections of a CC blade are advantageous for blade structural design being inherently more efficient structurally than conventional aerofoils which have elongated trailing sections often ending in a sharp edge. A simplified analysis indicates that the second moment of area of an elliptical section of constant wall thickness is ~ 35% greater than a symmetrical aerofoil with the same chord width, same wall thickness and same maximum section thickness. The major issue with the CC blade is then the design of the slots and preserving the slot gap dimensions in operation with elastic deformation of the blade. The most direct method of controlling slot height is to use fasteners (rivets, bolts) with precise thickness spacers to fix the two nozzle mouldings together at discrete intervals. This approach was used in helicopter technology for the MD900 Explorer NOTAR tailboom. It was found that the airflow disturbance resulting from a large number of small fasteners was less than for a small number of broader connecting straps. The fasteners would typically amount to a few percent blockage and negligible interference to the flow. More sophisticated designs with variable slot height controlled by micro-actuators can be envisaged and may be advantageous but can only be considered once the more fundamental aspects of design and operation of a CC rotor have been mastered.

The pressurisation of the jets will most probably be achieved using high efficiency variable pitch axial fans housed in the hub or blade root end. This could be a multiple stage compressor type of design as it is beneficial to deliver a relatively high-pressure output to the outermost CC sections. Unlike many fan applications which are essentially in steady state operation with slow changes in output demand, the fans/pumps will need to operate dynamically with fast response.

PRELIMINARY RESULTS

The preliminary design of CC rotor has CC sections over the outer 75% of span and conventional sections inboard which contribute very little power as the inner 25% of span includes the hub and primarily structural parts of the blade. The CC rotor design is for a tip speed ratio of 7.5 and an axial induction of 1/3. These parameters are unlikely to be optimum in terms of aerodynamics, loads or cost of energy but were chosen as a natural starting point to investigate the potential of CC rotors.



6 Power curve comparisons

Fig. 6 compares the power curves of this baseline design (100m diameter, 3MW rated power in ideal variable speed performance with a rotor Cp of 0.48) with a similar design expanded by a factor of 1.3 in rotor diameter alongside a CC design also expanded in diameter by a factor of 1.3. The CC rotor produces about 33% more power than the baseline which is much less than the 69% that would result if there were no pumping power demand and Coroilis braking power but crucially this power gain can be expected without any increase in design driving loads and consequently no impact on the system costs beyond the CC rotor itself.

Table 1 provides an overview of the power production components of the expanded CC rotor (130 m diameter) for steady state operation in ideal variable speed mode at the design tip speed ratio of 7.5 in a wind of 10 m/s. Power is produced by the augmented lift of the CC blade elements and negative drag due to jet reaction over the outer 75% span and also produced to a slight extent by the conventional sections of the inner 25% span. The rotor output power is however reduced by the Coriolis braking effect associated with the jets moving radially in a rotating reference frame. The net rotor power is then reduced by the drive train efficiency to give the electrical output from the rotor and the net power produced is this minus the required pumping power.

Table 1 Components of power production

Power	kW
CC blade elements power from lift	4016.9
CC blade elements power from negative drag	200.9
CC jet power from Coriolis force reaction	-234.7
Net power from CC sections	3983.1
Power from standard blade sections	65.5
Rotor net power	4048.5
Electrical power produced from rotor power	3765.1
Pumping power requirement	900.6
Gross electrical power delivered to grid	**2864.5**

FURTHER DEVELOPMENT OF CC ROTOR DESIGN

This design is steady state using a simplified approach and may possibly be far from optimum. There are very many variables to consider in attempting optimum design. Among them are;

- design tip speed ratio affecting blade solidity, loads and structure optimization
- optimum axial induction (distribution) affecting blade design lift and pumping power
- extent of span of CC elements
- extent of variation in slot height and in section pressurization
- rotor diameter expansion factor relative to a conventional baseline obviously affecting energy gain but also the issues in load regulation to baseline levels

A relatively low axial induction may be beneficial as has been explored for conventional rotors with standard aerofoils [4]. This would reduce the design lift and pumping power demand for the CC aerofoil sections. The next stage is to develop a dynamic model of system performance which may be essentially quasi-static. The response to turbulent wind could be based on comprehensive steady state aerofoil data as a function of angle of attack, pitch angle and slot momentum coefficient with or without accounting for unsteady aerodynamic effects such as stall hysteresis or induction lag. With that in place, a preliminary CC rotor design may be developed with energy gain and load regulation capability over a wide range of design load cases confirmed. Specification of the system for jet pressurization is then the focus in order to develop a preliminary view of the cost impact on the rotor system. Cost of energy modelling can focus on rotor structure and pressurisation system costs as there will be no downstream cost impacts on the system components beyond the rotor except in respect of O&M of the added pressurisation system.

It is also possible to have constant chord CC sections over a large part of the outer blade span. Although complex profiles are readily made in composite materials, there could be manufacturing cost benefit in having the section with slots completely uniform. In relatively high tip speed ratio designs, there is little need for twist or taper in the outboard blade sections.

CONCLUSIONS

This preliminary investigation of the potential of circulation control for large horizontal axis wind turbines indicates;

a) use of CC aerofoils enables a much expanded rotor diameter without exceeding the design driving loads of a baseline conventional rotor of standard diameter
b) diameter expansion by a factor ~ 1.3 seems feasible but will need to be confirmed by dynamic modelling of a candidate design over the wide range of load cases required by typical certification standards
c) preliminary steady state design suggests that power gains over 30% may be realized with the expanded CC rotor and perhaps significantly more as the design has not been optimized.

This suggests that the use of CC aerofoils on large HAWTs may be well worth consideration and further research.

References

[1] R. J. Englar, C. A. Applegate, “Circulation control – A Bibliography of DTNSRDC Research and selected Outside References,” DTNSRDC-84/052, Sept 1984

[2] G. S. Jones, R. D. Joslin, “Proceedings of the 2004 NASA/ONR Circulation Control Workshop”, NASA/CP-2005-213509, June 2005

[3] D. A. Wetzel et al., “Experiments on an Elliptic Circulation Control Airfoil” *J. Fluid Mech.* (2013), vol. 730, pp 99-144.

[4] P. K. Chaviaropoulos, S. G. Voutsinas, “Moving Towards Larger Rotors – Is That a Good Idea?” *EWEA Conf.* 2013, Vienna.